

STRUCTURAL BEHAVIOR OF DEEP REINFORCED CONCRETE BEAMS UNDER INDIRECT LOADING CONDITION

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ABSTRACT

This study investigates the structural behavior of indirectly loaded deep reinforced concrete (RC) T-beams. A total of 21 deep RC T-beams were divided into three groups according to the ratio of shear span to effective depth. Beams without web reinforcement were tested under indirect point loading applied via central intersecting members until shear failure. Experimental results indicate that indirectly loaded deep beams can carry additional load after diagonal cracking is initiated. The performance of these beams is associated with 3D non-linear finite element analysis that involves discrete reinforcement modeling. This modeling process is performed using ANSYS 12.1. Appropriate numerical modeling approaches are recommended, experimental load-deflection responses are compared in relation with FEA. The behavior of beams was observed under loading. Ultimate loads, deflection responses, and crack patterns are recorded as well. The numerical modeling results agreed with the test results for the beams.

KEYWORDS: Deep T-Beams, Indirect loading, Shear Span-To-Effective Depth Ratio

INTRODUCTION

The overall depth of reinforced concrete deep beam is considerably deeper than that of normal flexural members. Furthermore, the value of the thickness of deep members is significantly smaller than that of either depth or span. Winter[1], Park and Paulay[2], and Fereig and Smith [3] called members of this type deep beams. In such beams, the shear span/effective depth (a/d) ratio is less than 2 for simply supported beams and less than 2.5 for any span of continuous beams. Nawy[4] classified continuous RC beams with a/d ratio not exceeding 2.0 to 2.5 as deep beams. American Concrete Institute Building Code 318-11[5] classified as deep beams those with clear spans that are less than or equal to four times the total depth of the members depth or whose support faces are subject to concentrated loads with values within twice the member depth, as well as beams that are loaded on one face and supported on the opposite face so that compression struts can develop between the loads and the supports. Two loading cases are encountered by simply supported deep beams, namely, direct and indirect loading. In the former, external loads are applied perpendicular to the surface of a member in the direction of the member centroid (for example, traffic loads acting on deck units). In the latter, external loads are applied to the sides of members and away from the centroid, as denoted by the headstocks that support beams on the side faces of nibs[6]. Deep RC beams have been widely used in high-rise buildings as load-distributing structural parts of transfer girders, wall footing, foundation pile caps, floor diaphragms, and shear walls, among others.

Nonetheless, the performance of indirectly loaded deep RC beams is rarely investigated. Fereig and Smith [3] studied the behavior of indirectly loaded RC beams with short shear spans under loading and supporting

conditions. External loads are placed via shear brackets on the sides of the beams. Crack widths and deflections are more rarely encountered in direct loading than in indirect loading given beams with $a/d = 0.5$ or 1.0 . Moreover, these widths and deflections are more often experienced during indirectly loading near the bottom than near the top. Beams with web reinforcement generally exhibited narrow cracks, as well as few deflections and mild tensile steel strain. As per previous test results, arch action tendency was low for beams with $a/d=2$ than for beams with $a/d= 0.5$ and 1.0 . Ferguson [7], Taylor [8], and Neville and Taub [9] performed experiments on short shear span beams under indirect loading conditions. In these experiments, a/d ratios are 1.35, 1.64, and 2.09 respectively. The results indicate that a large portion of the additional strength associated with small a/d ratios has been lost. Similarly, Kalyanariman et al. [10] conducted experiments on two single-span deep beams with flanges that were indirectly loaded via side arms. The tensile stress in steel was non-uniformly distributed over the length before diagonal tension cracks were formed. Once such cracks formed, this stress gradually became uniform because of the tied arch action commonly encountered in deep beams. The experimental results showed that the shear strength of indirectly loaded deep T-beams could be a maximum of 70% higher than that of indirectly loaded deep rectangular beams. Kong [11] and Kalyanariman et al. [10] reported that the strong compression zone generated by the flanges in T-sections precludes shear compression failure in T-beams. As a result, shear strength capacity is increased. Many parameters affect the strength of deep beams, including a/d ratio, loading and supporting conditions, the extent and arrangement of tensile and web reinforcement, beam proportion and shape, and concrete and steel properties. According to Mohammad [12], the failure behaviors of deep beams differ significantly from those of ordinary beams due to load transfer mechanism and geometry. The behavior of RC deep beams ($a/d \leq 2$ [13]) loaded in shear conditions also varies from that of shallow beams because of the arch action initiated after diagonal cracking. Denpongpan [14] also concluded that RC deep beams without shear reinforcement can bear shear force through this action, in which load is transferred directly to the support via diagonal compressive strut. As per the experimental works conducted by several researchers [7], [15], and [16], the mechanical behavior of indirectly loaded deep beams differs from that of directly loaded deep beams. Furthermore, shear strength and shear at the first diagonal tension crack are much lower for indirectly loaded deep beams than for directly loaded deep beams. This finding can be attributed to the lack of confining compressive forces in indirectly loaded deep beams.

In the present study, 21 indirectly loaded deep RCT-beams without web reinforcement are subjected to point loads applied via inter section members in the centers of the beams. The main variables are flange size, the overall depth of the beams, and a/d ratio. All of the tested beams fail in shear; nonetheless, no local failure is observed due to crushing of concrete under the loads or over the supports. During the testing period, cracks, strains, deflection, and ultimate loads are recorded. A detailed 3D finite element (FE) model of a typical deep RC T-beam under indirect loading is presented to evaluate shear performance, as well as to predict and validate the experimental test result obtained by the authors. This research is performed using the non-linear FE software package ANSYS to predict ultimate indirect loading capacity and to estimate the curve of the load—mid-span deflection relation. The accuracy of the analysis is validated by comparing the ultimate load and deflection results generated by the FE model against the experimental results. In addition, the analysis yields important findings on the resistance of deep concrete beams with flanges that are affected by indirect loading conditions. The experimental results confirm previous findings reported by Zhang N, Tan, KH [17], which postulate that the effect of beam depth significantly influences the shear capacity and ultimate load of deep beams. In summary, the experimental results indicated the significant effect of flange size and beam depth on the shear strength of deep, flanged RC beams under indirect loading.

EXPERIMENTAL PROGRAM

Specimen Details

A total of 21 simply supported, single-span deep concrete beams are divided into three groups with a/d ratios of 1.0, 1.4, and 1.8. Each group consists of seven specimens; six had an overall height (h) of 300 mm, whereas the remaining specimen was 400 mm high. All of T-cross section beams exhibited a web thickness (b_w) of 120 mm; flange widths (b_f) of 240, 300, and 360 mm; and flange depths (h_f) of 60 and 90 mm. The specimens also contain rectangular central intersecting member with the same overall depth as the beams depth (300 mm). The width is (120 mm) and length is equal to the flange width of the beams. The beams are tested to failure under indirect point loads on the mid-span. The details and dimensions of the beams are provided in Table 1 and in Figure 1. All main beams are single span without shear reinforcement. The beams are designed to fail in shear; suitable tension reinforcement is provided to prevent flexural failure. The design compressive strength is obtained for cylindrical specimens with dimensions of 300 mm (height) \times 150 mm (diameter) in accordance with standard C 39 of the American Society for Testing and Materials [18]. The value of f_c' is derived from the mean values of three concrete cylinders cured under the same conditions for 28 days and tested on the same day of the specimen testing. The measured compressive strength of the employed concrete is 25 MPa, and the slump is approximately 120 mm [10, 19]. Two types of reinforcement are used in the specimens, namely, a deformed steel rebar for longitudinal reinforcement and a plain round steel rebar for flange and web reinforcement of intersecting member. The main reinforcement is provided by deformed steel bars with a diameter of 12 mm with yield strength of 270 MPa. The bars are anchored behind the support with sufficient length [20] and with a 90° bent to prevent anchorage zone failure. Stirrups with a diameter of 6 mm are located at the supports of the RC T-section beams and at the areas on which loads are applied. The material properties of stirrups and the main reinforcement are shown in Table (2). The values are averaged from three 600-mm long steel bars. Bearing plates that are 120 mm wide, 10 mm thick, and 120 mm long are positioned at the loading and supporting points to prevent local crushing failure in the concrete, as illustrated in Figure 2. The specimen notation is typically written as "TB1Gr1", where TB1 is the number of beams in the series of TB1, TB2, ... TB7 and character (Gr1, Gr2, and Gr3) denotes the a/d ratios of 1.0, 1.4, and 1.8, of the three groups.

Instrumentation and Test Setup

The typical experimental setups and arrangement for tested beams are displayed in Figures 3 and 4. A steel spreader beam controls the two equal point loads. This beam is situated on a two-pin support that is placed on top of the beams. Torsee's Universal Testing Machine was used to apply the load; this machine has a capacity of 2000 kN. Mid-span deflections are measured by an accuracy dial gauge (ELE type) with 0.01 mm accuracy. A capacity of 30 mm is assigned to the area underneath the center of the bottom faces of the specimens. The beams are loaded from top via the intersecting member at the center of the span of the beams. Load was applied incrementally; at each increment, the total load applied to the beam, the mid-span deflection, and the crack width are measured. Specifically, crack width is measured using a hand microscope, plotted, and marked. The test is terminated when the total load on the specimens begins to collapse.

Table 1: Details of the Tested Beams

Table2: Material Properties of the Rebar and Stirrups

Type	Yield Strength (MPa)	Ultimate Strength (MPa)	Modulus of Elasticity (MPa)
D6	450	560	200000
D12	330	520	200000
D16	330	600	200000

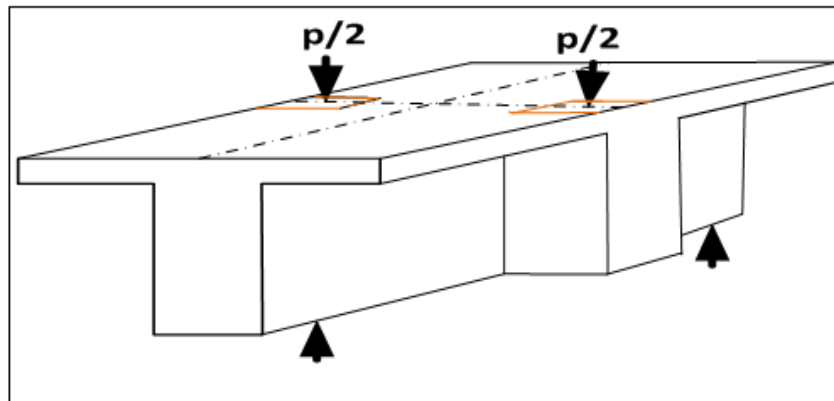


Figure 2: Indirect Point Loads

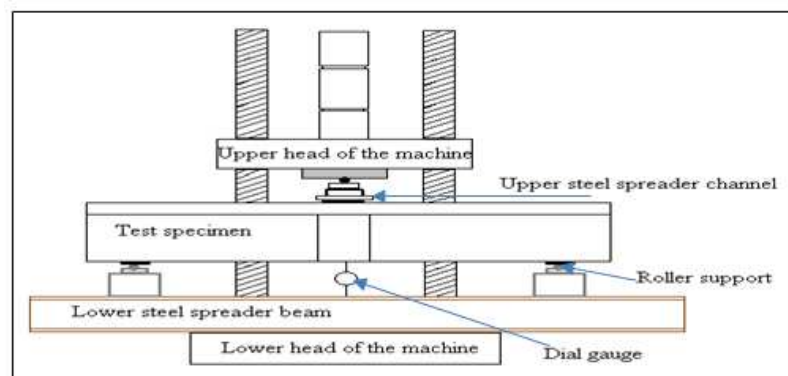


Figure 3: Test setup



Figure 4: Test arrangement

EXPERIMENTAL RESULTS

Behavior of Beams Underloading and Crack Patterns

The crack patterns of the three series of specimens showed that a significant part of the load is transferred to support through compression struts as shown in figure 5. This load transfer mechanism induces a common type of failure in deep beams [12, 21]. Figure 5 presents crack patterns, observed that when the load is increased inclined cracks developed in the shear span region. After internal forces are redistributed the beams sustain the additional load through arch action. All of the tested beams fail in shear when the diagonal shear cracks widen. Nonetheless, no local failure is observed due to the crushing of concrete under the load or over the supports. The main bars are provided with adequate end anchorage. Therefore, no anchorage failure is encountered during testing. In beams with a/d ratio of 1.0, the first diagonal crack is generated with a thud between the applied load and the support at mid-depth. Moreover, a few fine, inclined cracks are observed at the mid-depth of the loading path that is transmitted to the support. These cracks do not bridge with one another. A major inclined crack is widened at failure load. Beams with a/d ratios of 1.4 and 1.8 display similar behavior; however, the formation of inclined cracks is preceded by the development of a few inclined cracks near the intersecting member at the bottom of the main beams. Failure was suddenly induced by the extension of the diagonal crack through the compression flange.

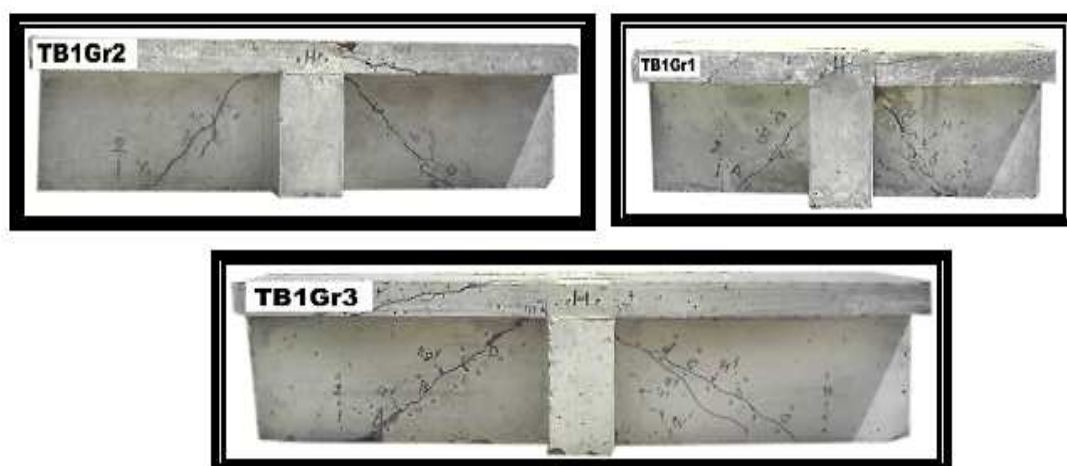


Figure 5: Crack Pattern of Test Beams

Inclined Cracking and Ultimate Loads

The inclined cracking and ultimate loads are listed in Table 3. The former is defined as the load at which the first major inclined crack is initiated in the shear span. When inclined cracks are generated, deep beams develop tied arch behavior (arch action). This behavior can improve the shear strength of such beams [21]. In group (1), beams TB2, TB4, and TB6 exhibited 37%, 38%, and 10% higher ultimate loads, respectively, than beams TB1, TB3, and TB5. In group (2), beams TB2, TB4, and TB6 reported 10%, 15%, and 26% higher ultimate loads, respectively, than beams TB1, TB3 and TB5. In group (3), beams TB2 and TB4 displayed 11% and 10% higher ultimate loads, respectively, than beams TB1 and TB3. This increase in the ultimate loads of beams with high flange depth is attributed to the strong compression zone generated through increasing flange depth. The reserve strength of the beams is defined as the ratio of the difference in ultimate load and diagonal cracking load to diagonal cracking load [22]. This strength is expressed as a percentage and measures the reserve strength beyond the inclined cracking load [23]. This strength decreases when a/d ratio increases, as

shown in Table 3. As per a comparison of the beams in groups 1, 2, and 3, ultimate load-carrying capacity increases by 67% in beams with flanges that are 60mm deep and 360mm wide when a/d ratio is reduced from 1.8 to 1.0. This capacity increases by 80% in beams with flanges that are 90mm deep and 360mm wide. The other beams exhibit similar behavior. This increase is attributed to the increased contribution of arch action-induced shear transfer in beams with low a/d ratio and is evident when flange depth increases as shown in Figure 6. Figure 7 displays the effect of beam depth on the shear strength of the three groups. Shear stress notably decreases with an increase in beam depth. Figure 8 presents the loads versus crack width for the three groups. Crack width increases successively during testing. At the same load level, beams with deep flanges exhibit narrower cracks than beams with shallow flanges. The same tendency is observed with the effect of overall depth; however, the opposite tendency is noted for a/d ratio. Flange width exerts a weak effect on the widths of major inclined cracks.

Effect of Flange Depth

Table (3) shows that maximum load-carrying capacity increases with flange depth (in the same group). To eliminate the effects of the variation in concrete compressive strength on ultimate loads, non-dimensional quantity ($P_u/bhf_c' = R$) was calculated and the results included in Table (3). As illustrated in Figure 9, beams with similar flange width and 90-mm deep flanges exhibited increased ultimate loads (with the same a/d ratio). This increase is attributed to the strong compressive zone generated by the increase in flange depth. Beams TB2Gr1, TB4Gr1, and TB6Gr1 display 34%, 3%, and 9% higher initial cracking load and 18%, 15%, and 20% higher ultimate load than corresponding beams TB1Gr1, TB3Gr1, and TB5Gr1. In groups 2 and 3, the variation in flange depth more significantly affected ultimate load than it did cracking loads.

Effect of a/d Ratio

The inclined cracking and the subsequent failure of deep RC beams are strongly affected by the relative magnitudes of shearing and flexural stresses [24]. This effect may be conveniently considered to be a function of a/d ratio. The distribution of stresses in the beams subject to indirect loading suggested a tendency toward arch action after cracking but not toward pure arch action because the force in the tension reinforcement is not constant through the span [10]. The relations between (a/d) ratio and the measured ultimate load for tested beams are presented in Figure 6. Ultimate load is increased considerably by reducing the a/d ratio, because the property of arch action is low given a high a/d ratio [3].

Load-Deflection Response

The curves of load- versus mid-span deflection of the tested beams are plotted in groups and displayed in Figure 10. The slope of the curves changed after the inclined crack was formed, because the onset of the first major inclined crack reduced beam stiffness significantly. Beams with 90-mm deep flanges exhibit smaller deflections than beams with 60-mm deep flanges at the same load level and with the same a/d ratio. Moreover, 400-mm deep beams display smaller deflections than 300-mm deep beams. An increase in flange width increases deflection, as observed in the three groups.

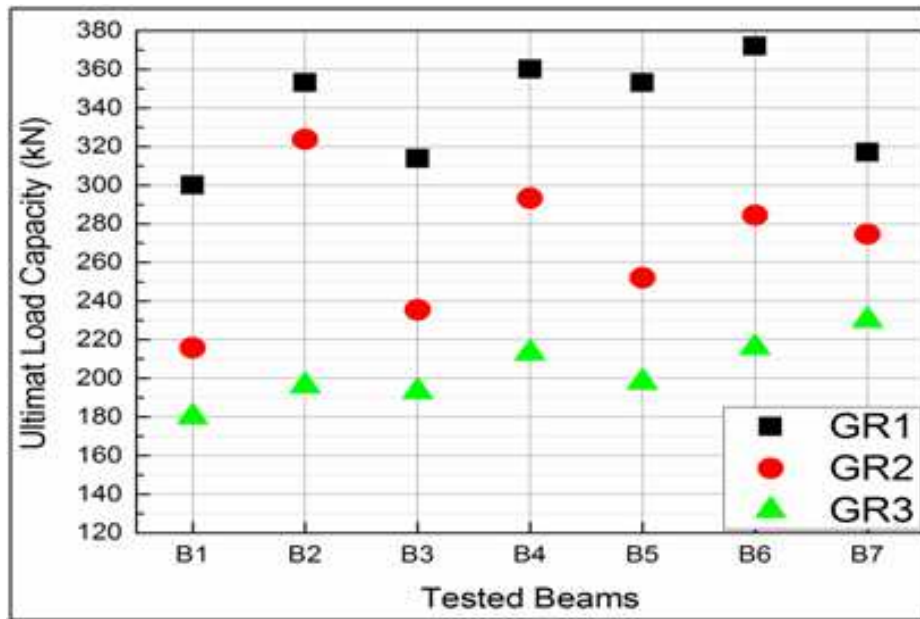


Figure 6: Ultimate Load-Carrying Capacity of the Tested Beams given Different a/d Ratios

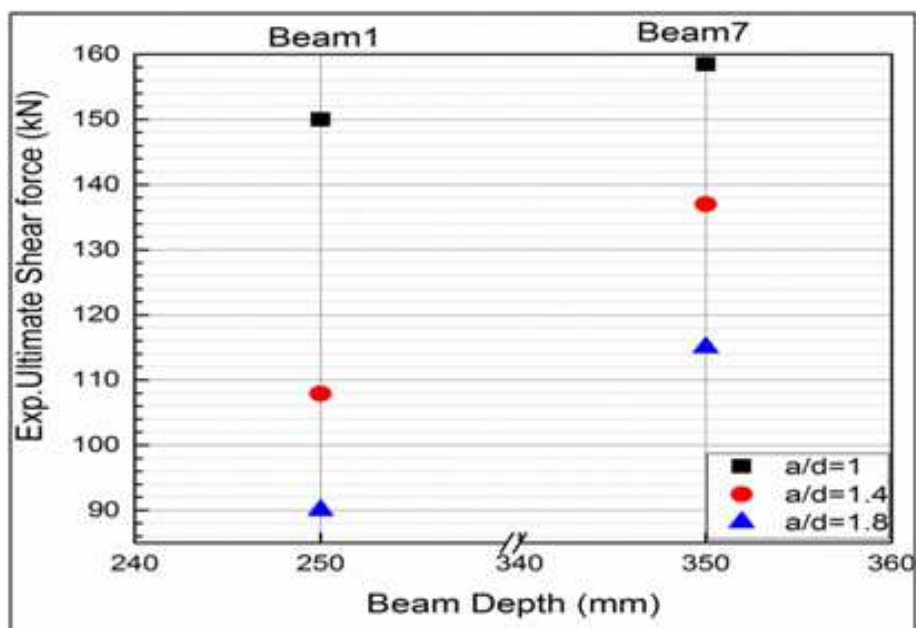


Figure 7: Effect of Beam Size in the Three Groups

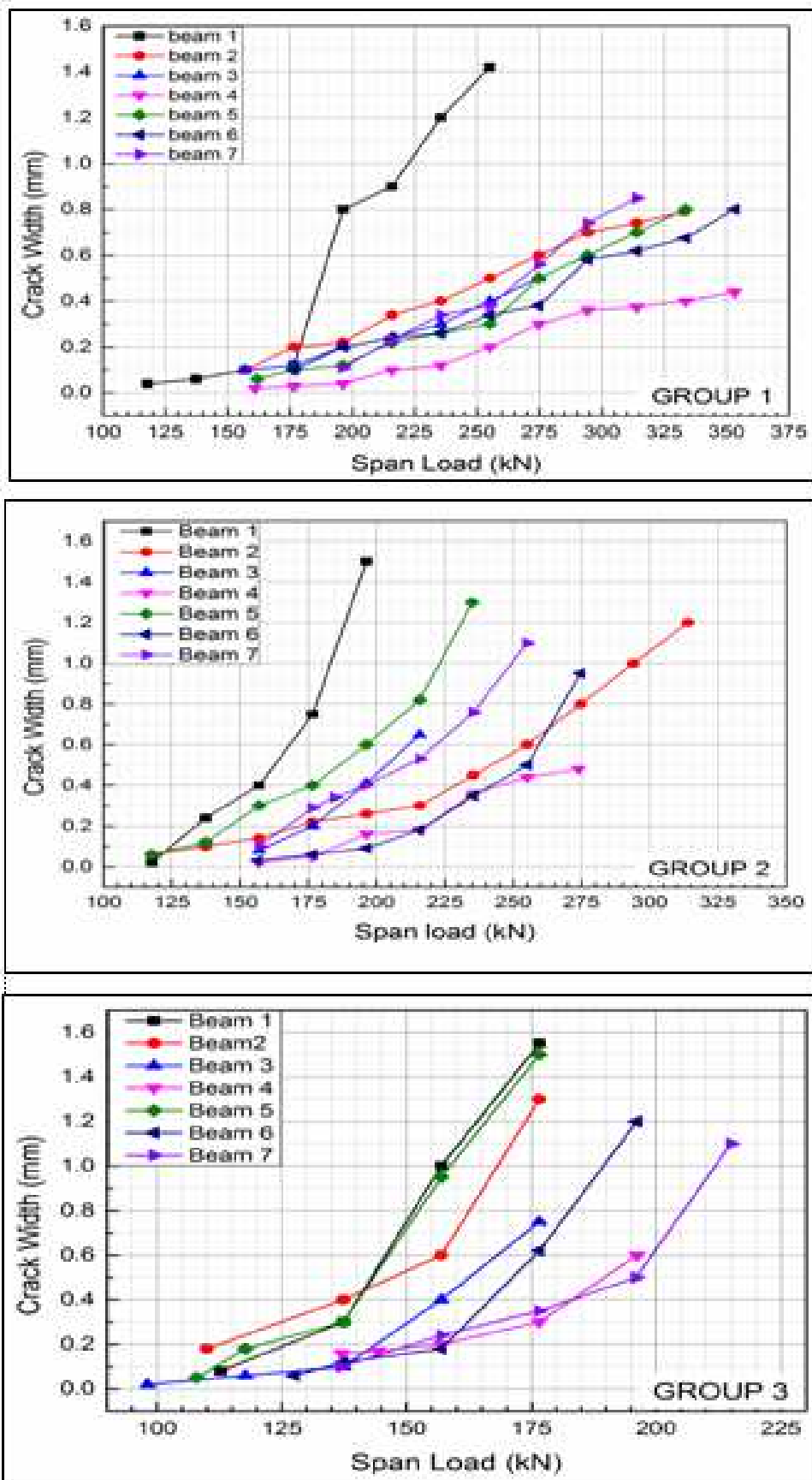


Figure 8: Load versus Crack Width in the Three Group

Table 3: Inclined Cracking and Ultimate Load in the Experiment

Beam no.	Span load (kN)		P_{cr}/P_u	P_u/bhf_c' (R)	$\frac{P_u-P_{cr}}{P_{cr}} \times 100$
	Inclined Cracking P_{cr}	Ultimate P_u			
Group (1) a/d = 1					
TB1Gr1	117.70	300.00	0.39	0.27	155%
TB2Gr1	156.96	353.00	0.44	0.37	125%
TB3Gr1	156.96	313.90	0.50	0.29	100%
TB4Gr1	160.96	360.00	0.45	0.40	124%
TB5Gr1	161.86	353.00	0.46	0.32	118%
TB6Gr1	176.95	372.78	0.47	0.35	111%
TB7Gr1	196.96	317.80	0.62	0.23	61%
Group (2) a/d = 1.4					
TB1Gr2	117.70	215.82	0.55	0.21	83%
TB2Gr2	117.70	323.73	0.36	0.23	175%
TB3Gr2	156.60	235.44	0.67	0.26	50%
TB4Gr2	156.96	293.32	0.54	0.30	87%
TB5Gr2	117.70	252.12	0.47	0.23	114%
TB6Gr2	156.60	284.50	0.55	0.29	82%
TB7Gr2	156.96	274.68	0.57	0.26	75%
Group (3) a/d = 1.8					
TB1Gr3	112.80	180.00	0.63	0.19	60%
TB2Gr3	110.00	196.00	0.56	0.21	78%
TB3Gr3	98.00	193.00	0.51	0.20	97%
TB4Gr3	137.00	213.00	0.64	0.22	55%
TB5Gr3	107.90	198.00	0.54	0.22	84%
TB6Gr3	127.50	215.80	0.59	0.22	69%
TB7Gr3	137.00	230.00	0.59	0.26	68%
		Average ratio	0.53		
		Standard dev.	0.08		

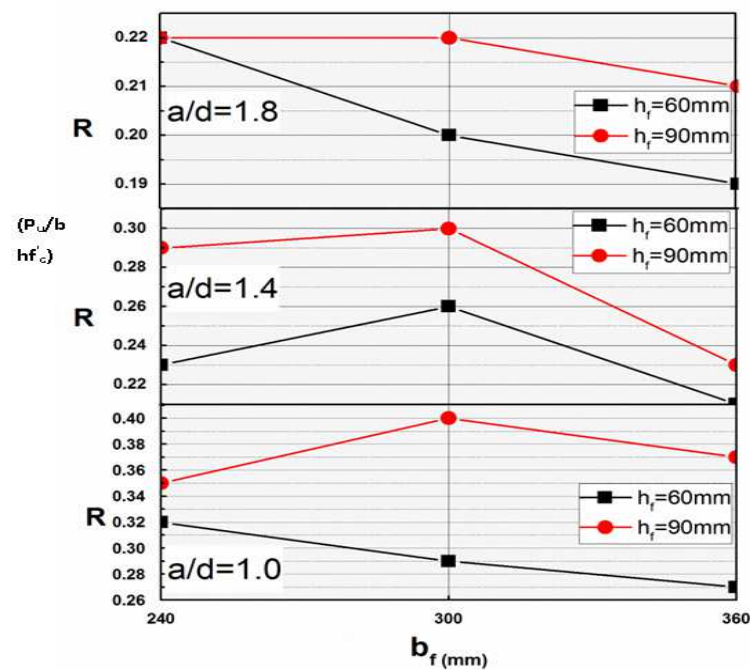


Figure 9: Effect of Flange Size on the Tested Beams

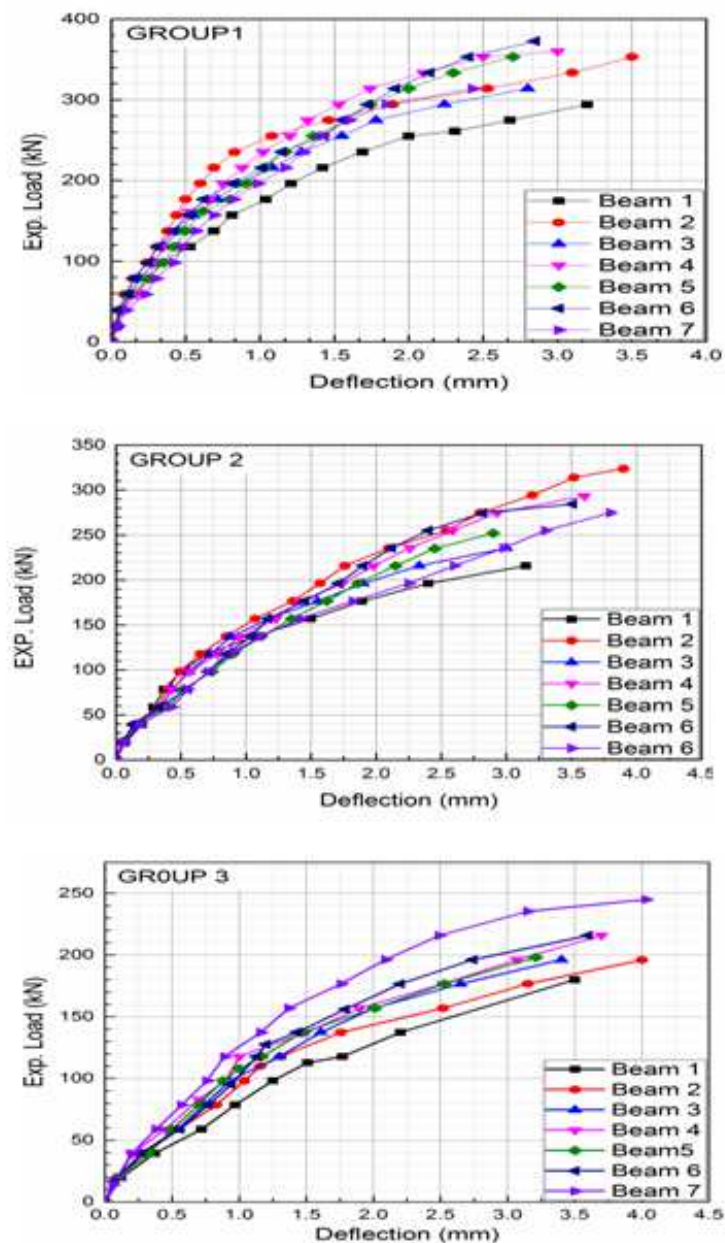


Figure 10: Load-Mid-Span Deflection of the Tested Beams

FINITE ELEMENT MODEL

The FE model considered in the current study has the same geometry, dimensions, and configuration as the test specimens. Table 1 shows the geometries of the models of the three groups of T-deep beams. The details are provided in Figures 1 and 2. FE analysis is performed using ANSYS 12.1 in the current study [25]. A quarter of the full beam was modeled according to the symmetry of the materials, loading, and boundary conditions. This model was analyzed on the basis of the code of commercial FE ANSYS [25]. The benefit of building quarter models of this construction is that the total number of elements is reduced to save much computational time. The selected element types in ANSYS 12.1 [25], by Wolanski [26], and by Kachlakev [27] are the 3D 8-Node Reinforced Concrete Solid and the structural element, SOLID65 to model concrete material for non-linear reactions of brittle materials on the basis of a constitutive model for concrete

triaxial behavior. This element covers a smeared crack in tension zones and a crushing response in compression zones. The material used in steel reinforcement is a 3D two-node structural bar given the structural element LINK8. The supports and area at which loads are applied on the steel plate are denoted by a 3D eight-node structural solid given structural element SOLID45. The models of the different materials were used by Wolanski[26], Kachlakev[27], Mohammed [28], and Hemmaty[29] for structural stress analysis. The FE model is shown in Figure 11. Concrete is modeled according to the standard non-linear constitutive material model of concrete implemented within ANSYS 12.1 software. This model is based on the formulation developed by Williams and Warnke[30]. The non-linear response of a RC structure is commonly produced by three major factors: concrete cracking, concrete non-linearity in compression, and the plasticity of the steel reinforcement rebar. Prior to the formation of the first crack, the behavior of concrete is linear; afterward, this behavior becomes non-linear. The values of the coefficient of shear transfer across a crack varies between complete shear transfer and no shear transfer at the cracked section depending on the crack texture, as per Hemmaty[29].

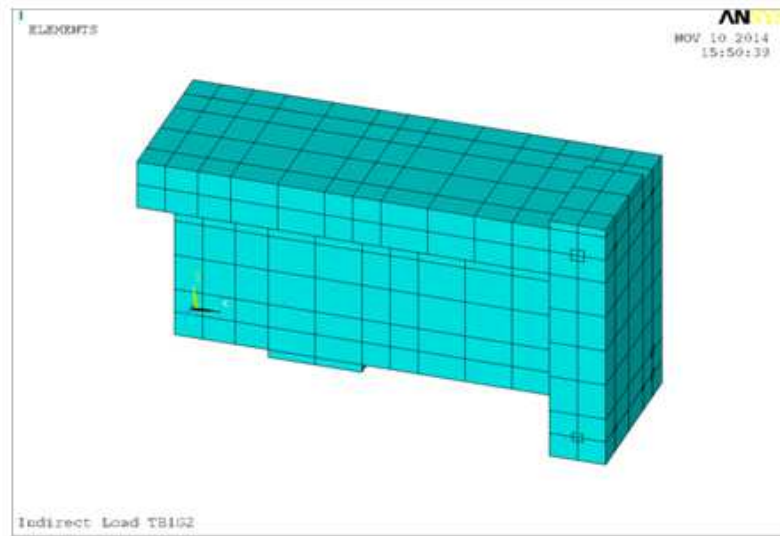


Figure 11: FE Model (Isometric of the FE Model of One Quarter of the Beam and Mesh)

Numerical expressions, that is, Equations (1), (2) [31], and (3) [32], were used to construct the uniaxial compressive stress—strain curve for compressed concrete used in the present study.

$$f = \frac{E_c \epsilon}{1 + \left(\frac{\epsilon}{\epsilon_0} \right)^2} \quad (1)$$

$$\epsilon_0 = \frac{2f_c}{E_c} \quad (2)$$

$$E_c = \frac{f}{\epsilon} \quad (3)$$

Where f = stress at any strain ϵ ; ϵ = strain at stress f ; and ϵ_0 = strain at ultimate compressive strength.

The first point of the curve must satisfy Hook's law in the implemented multilinear isotropic stress—strain relationship. Figure 12 shows the simplified compressive uniaxial stress—strain relationship that is considered in the current study[33].

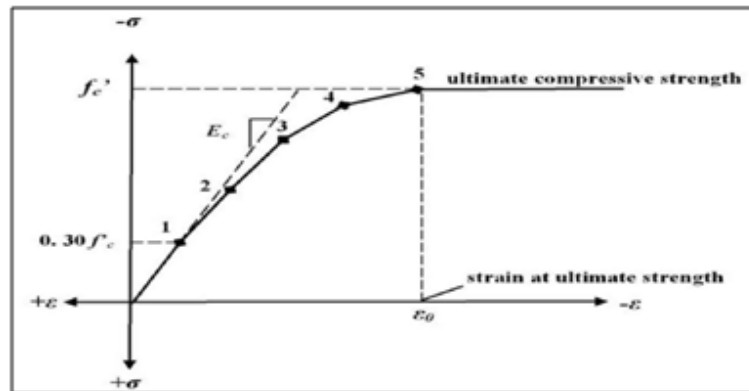


Figure 12: Simplified Compressive Uniaxial Stress Strain Relationship in Concrete

Inclined cracks first develop in beams with $a/d \leq 2.5$. Once internal forces are redistributed, the beams accommodate the additional load through arch action[20]. The tensile stress—strain response of concrete as a linear elastic relationship and the stiffening of RC tension after cracking are represented by a linearly descending branch until the point of cracking stress. The tension-stiffening effect is considered because the cracked concrete can still handle slight tensile stresses in the normal crack direction. This result is generated in ANSYS by assuming the gradual release of the concrete stress component normal to the cracked plane[34]. The relation of uniaxial stress versus strain for reinforcing steel rebars is idealized as a bilinear curve. This curve represents elastic—plastic behavior with strain hardening. This relation is assumed to be identical in terms of both tension and compression as per the European Committee's[35] criterion of von Mises plasticity yield. This scenario is displayed in Figure 13.

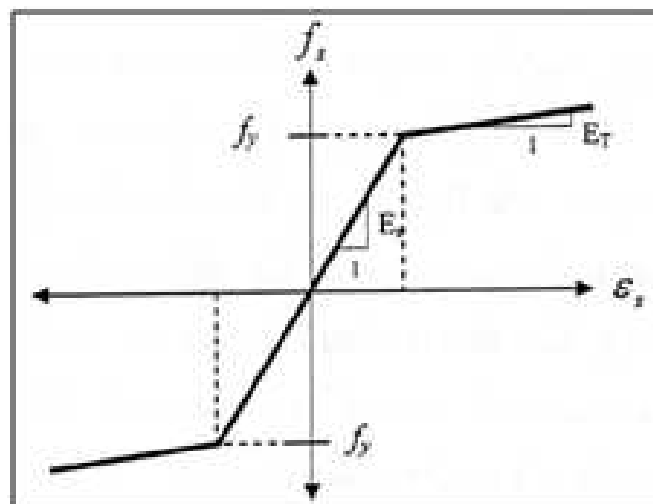


Figure 13: Modeling of Reinforcing Bars

Figure 14 depicts the typical 3D failure surface of concrete materials. The stress on this surface is biaxial or nearly

biaxial, and the most significant nonzero principal stresses are in the x and y directions [36]. When these principal stresses are both negative in value (compressive), the failure mode is a function of the sign of the principal stress in the z direction. Three failure surfaces can be generated as in Figure 14. The principal stresses in the z direction are slightly greater than zero (cracking), equal to zero (crushing), and slightly less than zero (crushing). When one or both of the principal stresses in the x and y directions are positive in value (tensile), the failure mode is cracking. This mode is illustrated in Figure 14 [36]. During FE analysis, cracking was induced in a concrete element when the principal tensile stress in any direction is observed beyond the failure surface. The elastic modulus of the concrete element is set to zero after cracking in the direction that is parallel to the direction of principal tensile stress. Crushing occurs when all principal stresses are compressive and are beyond the failure surface [36]. Consequently, the elastic modulus is set to zero in all directions. Furthermore, the value of the local stiffness of the element becomes zero. This value induces significant displacement and, subsequently, divergence in the solution.

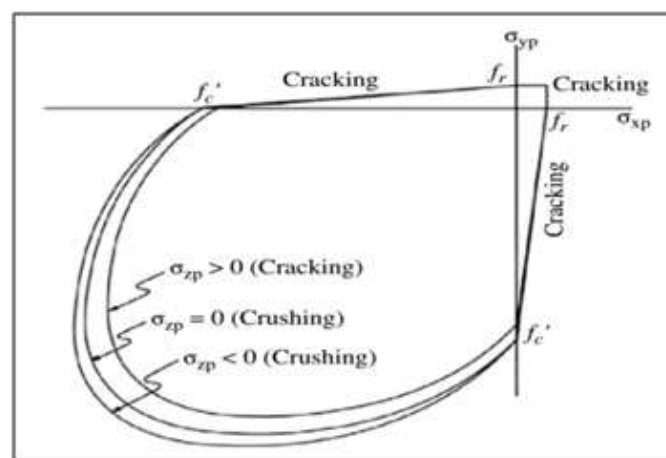


Figure 14: 3D Failure Surface for Concrete

In the current study, load is applied incrementally on a steel plate. The process is iterated to obtain a converged solution that corresponds to the loading stage under consideration. Newton—Raphson procedure is performed in full; the load is subdivided into increments of series loads that are applied in several steps. A stiffness matrix is formed at each iteration. This iterative procedure continues until a solution is convergent. The advantage of this procedure is that it may produce accurate results; nonetheless, the disadvantage lies in the significant computational effort that may be required to form and decompose the stiffness matrix. This scenario is presented in Figure 15. The beams and plates are modeled as volumes.

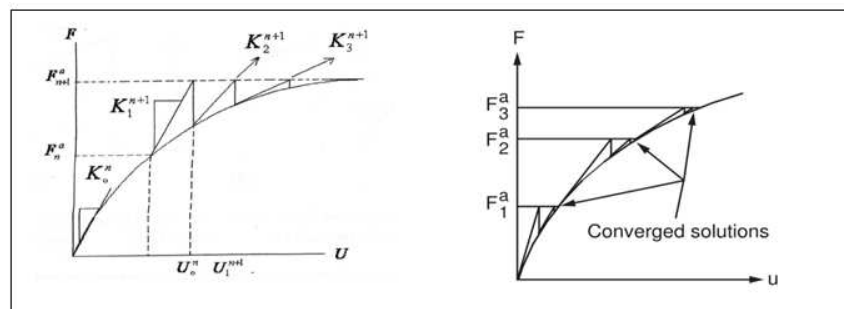


Figure 15: Incremental-Iterative Procedures and the Full Newton-Raphson Procedure

COMPARISON RESULTS

To assess the validity and predictability of the model, the experimental results are compared with the FE findings. Figure 16 shows typical measured and analyzed results predicted using FE ANSYS with the respect to the mid-span vertical displacement at the centerline of the cross section versus the applied indirect load. The advantage of the FE model is reflected by the fact that the numerical mid-span deflection is very close to the experimental data when all factors are well controlled. The curve of FE load-deflection response differs slightly from the experimental curve; this discrepancy may be explained by certain effects. First, micro cracks are existent in the tested concrete beams and can be formed through drying shrinkage in the concrete and/or beam handling. By contrast, the non-linear FE models do not contain micro cracks. Second, the bond between the concrete and steel reinforcement is assumed to be perfect in the FE analysis. However, this assumption is not true for the tested beams.

Figure 17 presents the crack patterns of the ANSYS models for comparison with those of the test beams. Figures 16 and 17 clearly indicate that the experimental results agree with the numerically predicted FE deflection findings. Although the model of nonlinear numerical analysis under-predicts the ultimate load carrying capacity slightly, the study results confirm the experimental and FE analysis results presented by Özcan et al.[37].

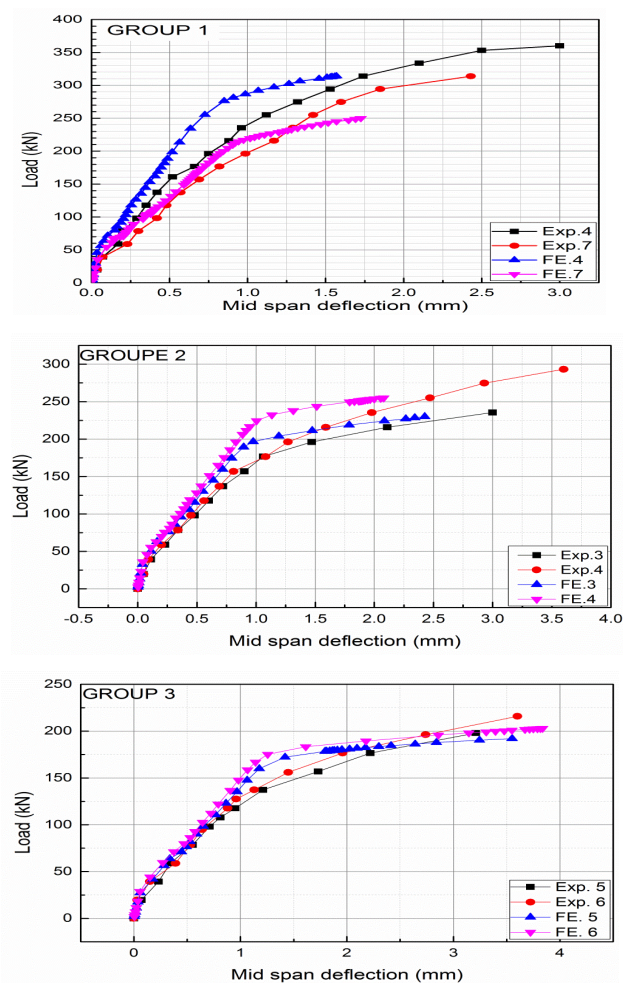


Figure 16: Load Versus Mid- Span Deflection Comparison
between Experimental and FEA

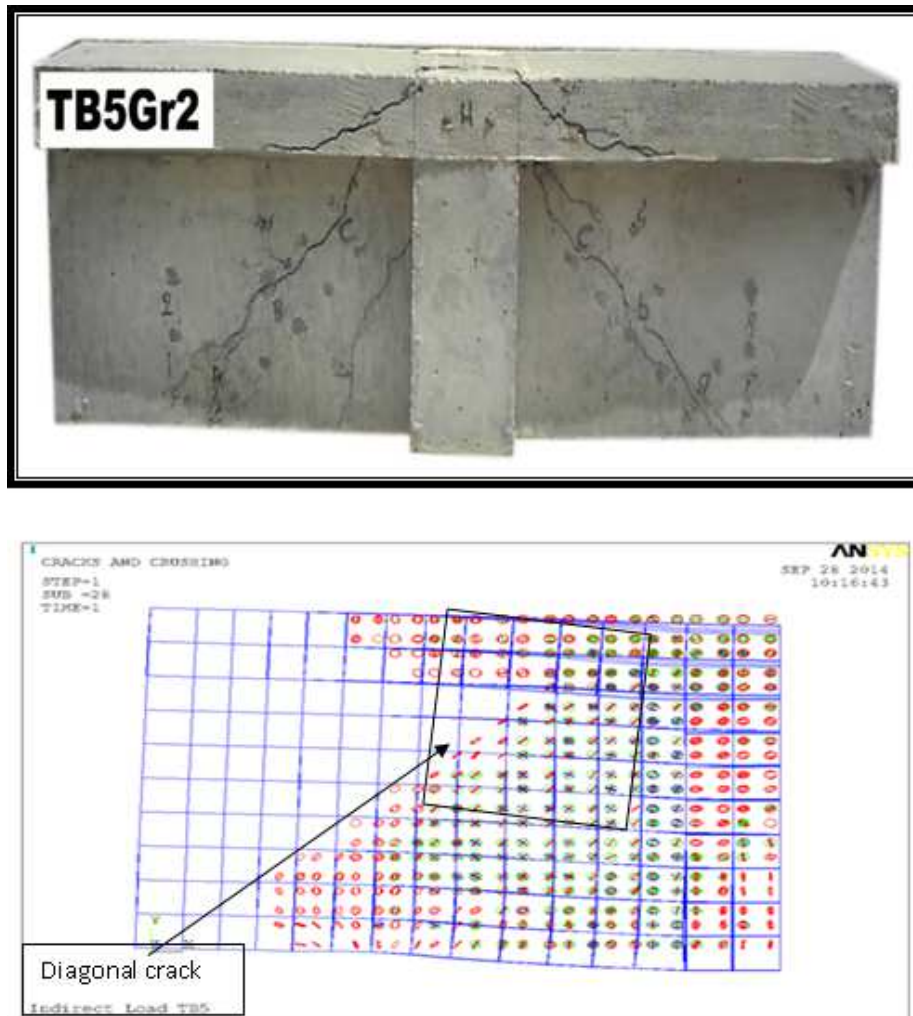


Figure 17: Crack Patterns at Ultimate Load as observed during Experiments and FE Analysis

CONCLUSIONS

The behaviors of indirectly loaded deep beams are examined through experiments and an FE model in this study. The results obtained are then compared. The tested beams are produced in a laboratory, and the beam model is loaded to the point of failure. Deflection and crack patterns are monitored as well. FE behavior was analyzed using the ANSYS program. Eight-node (SOLID65) solid brick elements were used to model the concrete. Internal steel reinforcement was modeled using Link 8 3D spar elements. The ultimate load of failure and the displacement predicted by non-linear FE analysis are close to those measured during experimental testing. The load–mid-span deflection curves of the specimen from the FE/ANSYS analysis agreed with the experimentally obtained curves. The crack distributions observed in FE analysis also agreed with the experimental results. On the basis of the evaluation, the experimental results, and the FE analysis findings for indirectly loaded deep T-beams, the following conclusions can be drawn:

- The stresses and deflections at the centerline of cross sections and the progressive cracking observed in the FE beam model are consistent with those measured in a deep RC T-beam.

- The failure mechanism of indirectly loaded deep T-beams is effectively modeled through FE analysis. Moreover, the predicted ultimate failure load is close to that obtained during experimental testing.
- The crack pattern showed that the webs of all of the beams functioned as simple struts between loads and supports.
- The mid-span deflections of the indirectly loaded, flanged deep beams are smaller and fewer than the permissible deflections specified by ACI Building Code (318-11). These deflections did not cause any problem at service load $P_u/1.5$.
- The increase in flange size enhances the cracking and failure load- carrying capacity. The enlargement of flanges also reduces the corresponding mid-span deflection at the same a/d ratio.
- Both ultimate and inclined cracking loads tend to increase with a decrease in a/d ratio to below 1.8.

GENERAL SYMBOLS

Table 4

Symbol	Definition
hf	Flange depth
bf	Flange width
a	Shear span
b_w	Web width
h	Overall depth of beam
l	Clear span
P_{cr}	Cracking span load
P_u	Ultimate span load
d	Effective depth of beam
f'_c	Cylinder compressive strength of concrete
f_{cu}	Cube compressive strength of concrete

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